THE DESIGN OF A TETHERED BALLOON SYSTEM TO EXPLORE THE MARTIAN ATMOSPHERE
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ABSTRACT

This study was carried out to investigate the feasibility of a balloon mission to Mars. The balloon package will go along with a future Mars lander mission as an instrument. Two mission concepts were considered: an atmospheric boundary layer measurement mission and a rover support mission. Both missions use a tethered balloon which will fly at an altitude of 100 metres, connected to a lander.

For the boundary layer measurements configuration, 10 instrument packages are placed along the cable. Each package includes a pressure, temperature, and humidity sensor. By spacing the packages along the cable, a profile of the atmospheric boundary layer can be made. Such a profile can be used for validation and improvement of Martian atmosphere models.

The rover support mission features a gondola suspended below the balloon. A camera is mounted in the gondola taking high-resolution images from an altitude of 100 meters, so that rover navigation is assisted.

This study has shown that a low cost and low risk balloon carrying instruments on a mission to Mars seems feasible and can carry out meaningful science.

1. PROJECT OBJECTIVES

Mars has always been an object of scientific interest, but not much is known yet about the atmosphere. Its composition is known, but the interaction between the surface and the atmosphere in the boundary layer is an interesting point of research. Up to now, in situ measurements in the atmosphere of Mars have only been carried out during entry and descent of landing vehicles or by surface dwelling systems. A balloon mission could carry out measurements in the atmospheric boundary layer. At the same time, such a mission can function as a technology demonstrator for lighter-than-air exploration of Mars.

A rover navigating the Martian surface can also benefit from a balloon mission. Instead of having the rover make images to map the environment (which is very time consuming), a balloon could carry a camera high above the rover and provide high-resolution images of the surface. High-resolution images will provide a surface map, and interesting areas are more easily discovered.

To clearly define the mission science objective the following Mission Need Statement (MNS) has been used:

Explore the Martian atmosphere and surface for at least 90 Martian days (sols) with a self-contained, low risk balloon system, as instrument on an Entry Descent and Landing System (EDLS).

2. MISSION ANALYSIS

Before the balloon system was designed, the balloon mission has been analysed to discover the system requirements. The following mission scenario has been used to analyse the balloon mission:

After the Entry, Descend, and Landing (EDL) vehicle has landed, the balloon instruments are checked to see whether they still function. When all systems are up and running the deployment will take place. The EDL system will then open and inflation of the balloon starts. After balloon inflation, the calibration of instruments will take place at ground level. These calibration values are used as reference data for further measurements. Following calibration the reel brake is released and the balloon ascends. At each step during these operations, checks are incorporated to ensure all operations are performed satisfactorily.

The position and altitude of the balloon are then determined and are consequently linked to the measurements performed. Depending on whether the relay station, EDLS or an orbiting relay satellite can be contacted the data will be stored on-board or transmitted.

After the balloon has been operated the system may go on gathering data or the measurements stop and disposal of the system is initiated. At the end of the life cycle, when there is insufficient power generated or the system is critically damaged, the system itself will initiate its disposal. To minimise the impact on the EDLS systems, the balloon will be brought back to the surface of Mars by initiating a controlled reeling in of the cable.

Now the functions needed to support the exploration are derived from the operations. First, the balloon has to deploy. Then the balloon system has to check the instruments and communicate with the EDLS. Furthermore the system should provide power and data handling for the on-board instruments.

From the mission objectives, operations, and functions a list of requirements can be defined, the most important requirements are listed below:

- The balloon is able to stay afloat in the thin Martian atmosphere
- The balloon system is protected against (UV) radiation and balloon out-gassing is prevented
- The balloon costs should be below €2 million
- The impact of the balloon on the Martian environment should be minimised.
- Measurements are taken for a period of at least 90 Martian days (sols).
- The balloon mission must be low-risk

For the atmospheric mission an extra requirement exists:

- The balloon is able to take measurements at different altitudes.

Also extra requirements are set up for the visual support mission:

- The gondola has sufficient stability to make clear images.
- The camera resolution must be high enough to recognise possible dangers for the rover.

3. DESIGN OPTIONS

During the initial design phase, many design options were considered for both the camera support mission and the atmospheric measurement mission. The main design option for these balloon systems was whether a free or a tethered balloon should be used. Eventually a tethered balloon has been selected, for reasons of communication and power provision. A free balloon mission would require its own power provision and communication system. The mass of the system would then become so large that the balloon mission would have to be a mission on its own, rather than serving as an instrument in a lander mission.

Other design options involved deployment of the balloon. For instance, one could choose to deploy during entry in the Martian atmosphere or for deployment after the EDL vehicle has already landed on the Martian surface. Deployment from canisters, using parachutes, atmospheric gasses and other options were considered. Since tethered balloons are used, analysis of the deployment showed that deployment from the Martian surface was most beneficial. Hence this deployment option has been used further-on in the design process.

Various power provision options were considered, power sources such as only batteries, solar energy and even nuclear energy were investigated. Research was also put into potential active and passive thermal control methods. Moreover, to select a suitable buoyancy gas, the statics of balloons with multiple compartments and various gasses were simulated. Different cable materials for the load bearing part of the tether were also investigated. For the camera gondola, many shapes were investigated, such as zeppelin-like constructions. The final designs for the two mission concepts are briefly described in sections 5 and 6, section 4 discusses the balloon and its deployment system.

4. BALLOON SYSTEMS

Both the atmospheric measurement mission and the camera mission will feature the same balloon deployment system and load bearing tether. Only the balloon used for the camera system will be larger than that for the atmospheric measurement balloon system, 3.34 m versus 3 m radius respectively. To provide lift, a balloon gas expanding under influence of solar heating may be used. During the night when there is no heating, the balloon will land on the Martian surface where its skin might tear due to interaction with the surface. Solely relying on the Sun for balloon lift would impose too much risk to the balloon, therefore a gas lighter than the Martian atmosphere is used. This also rules out an open balloon design.

Basically, there are two closed balloon types; a super pressure balloon and a zero pressure balloon. If the internal and external pressure is equal, the balloon is a zero-pressure balloon. On the other hand, if the internal pressure is higher than the external pressure, the balloon is a super-pressure balloon. The skin of a super-pressure balloon does not only need to take the loads of the payload, but also of the loads due to the pressure difference. Therefore, the skin of a super-pressure balloon needs to be thicker or made out of heavier material to accommodate this additional loading. Choosing a super pressure balloon would thus make the design heavier, but also more complex and prone to failure. This resulted in the selection of a zero pressure balloon for the final design. The balloon size, thickness, and gas type were varied and used to simulate a balloon with a varying payload mass. As a result, linear low-density polyethylene (LLDPE) [10] is selected as balloon skin material, with a thickness of 6 micron. The buoyancy gas of choice is helium, due to its low specific mass and inherent safety since helium is an inert gas.

The balloon deployment system is composed of a canister lid, reel, pressure system, and a balloon support structure. An overview of the system is given in figure 1, and the deployment sequence can be seen in figure 2. The canister lid opens and slides behind the box. Then, a specially designed supporting cone structure, made of Mylar [9] glued to the balloon, is inflated, helping the balloon unfold and reducing the risk of tearing the balloon material. The reel will be moved upward by 2 linear actuators, thus preventing contact between the cable and the edges of the canister. The balloon will be inflated with helium from a 400 bar pressurised tank made out of winded composite fibres [2]. The balloon gas will not be pumped into the balloon directly as this could cause rupture of the vulnerable balloon material. Instead the pressure is regulated by valves and tubes, slowly reducing the pressure before it reaches the balloon. When the balloon is inflated, the reel brake will be released, such that the balloon rises due to the lift. If the balloon ascends too quickly, the brake can be applied to slow the balloon down.

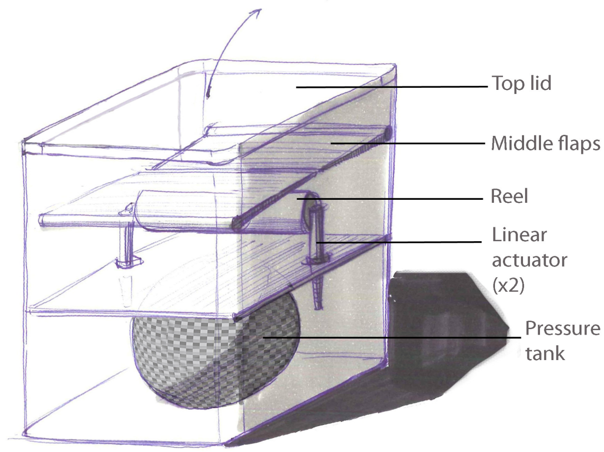
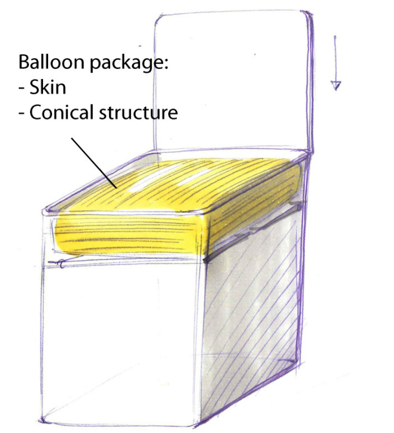


Fig. 1: Overview of canister.

The tether plays a major role in the balloon design. If it is broken, the balloon will float away. In that case the mission will fail, as communication and power provision to the instruments is then lost. Because the prevailing winds on Mars influence the position of the balloon and forces in the tether, a simulation was performed using Msc Adams and the “Kite and kite components” toolbox of ir. Breukels [1] to investigate the dynamics of the cable and balloon. Wind speeds were obtained from Martian databases, for instance the Mars Climate Database [6]. From the simulation the maximum force in the tether followed to be 300N. As a result, ultra-high-molecular-weight polyethylene (brand name DYNEEMA [3]) is chosen as the material for the load bearing part of the tether, because it has a higher strength to weight ratio main competitor Kevlar [4]. Analysis showed the required minimum radius of the cable to be 0.17 millimetre. Applying a safety factor of 2 and taking the next logical unit of cable production diameter resulted in a cable diameter used of 1 millimetre.

The tether is used for the power provision as well. The lander provides power and sends this through conducting cables to the balloon instruments. This way, the balloon payload mass is reduced and therefore also the balloon gas required to keep the balloon floating. After basic mass analysis and taking into account voltage loss, the lightest cable turned out to be an aluminium one. Copper was considered as well, but the mass of such a cable would be higher than that of an aluminium cable. Hence it was discarded.

In a similar way as the power provision, the communications and data handling subsystem sends its data via the conducting cable by using differential communication on the power line.



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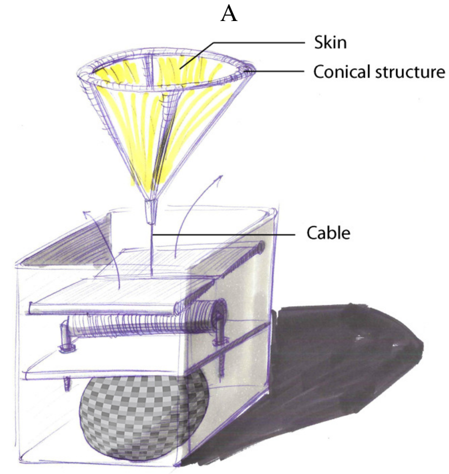

B

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Fig. 2: Balloon deployment process. Chronological from A to C.

5. DETAILED DESIGN CAMERA MISSION

In order to create useful images from a height of 100 meters, the on-board camera needs to have a high enough resolution to map the lander surroundings in sufficient detail. A trade off is made between resolution and mass, also taking into account the camera viewing angle. The camera selected from the trade-off is the MSSS (Malin Space Science Systems) ECAM C30 [7], which can distinguish objects with a resolution of 9 x 8 cm/pixel. The camera controller is supplied by the MSSS and the whole package is space ready.

The camera needs thermal control to stay within its temperature operating range. This is done by using a multi-layer insulation made of aluminised Mylar. The layers do not only provide a constant temperature during day and night, but also protect the gondola against UV radiation.

The gondola itself is made out of polyurethane and fibreglass. The whole package is wrapped in an aluminised Mylar space blanket. The space readiness of polyurethane is questionable, but since it is not a critical part of the gondola, it could be replaced by another lightweight material. To guarantee gondola stability, a ring could be used preventing the gondola from spinning. Other gondola suspension method can also be considered, see figure 3 for impressions on possible suspension options.

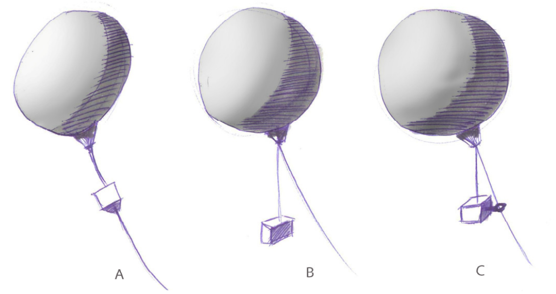

Fig. 3: Camera gondola suspension options.

6. DETAILED DESIGN ATMOSPHERIC MEASUREMENT MISSION

The atmospheric measurement package originally consisted of four types of sensors. These four sensors could measure five quantities, namely temperature, pressure, humidity, wind velocity, and wind direction. The sensors used for temperature (THERMOCAP) and humidity (HUMICAP) need all to be modified, but they are already qualified space-ready [5]. The pressure sensor is from MKS Instruments, but this sensor, the series 900 MicroPirani still needs a lot of modifications before it is space-ready [8]. The anemometer, which measures wind velocity and direction, was designed and used on the Beagle 2 mission. Thus the assumption is made that this sensor is also space ready [11].

The main reason for not including the anemometer in the atmospheric package is that the attitude and position need to be known for knowing the wind direction. The package would be too heavy if an attitude determination instrument would be installed; hence it is decided not to include an anemometer.

The sensors are placed on a printed circuit board, which also houses chips for data handling and power management. As depicted in figure 4, the chips are protected by a titanium cover on both sides, and are curved. The radius corresponds with the reel radius.

To measure at various altitudes, ten atmospheric packages are installed at pre-determined intervals along the tether.

Fig. 4: Atmospheric measurement package layout

7. RISK ASSESSMENT

The mission risks assessed may be divided into two categories: 'failure of the balloon mission' and 'failure of the lander mission'.

During the operations the balloon is not a stand-alone mission, but an instrument used by the rover. Among other risks, the highest risks posed to the balloon system are deployment failure and failure of the balloon skin. Both failure types would result in a lost mission. The risk of deployment failure may be mitigated by extensive testing, using safe life design and use of as much redundant parts in the deployment system as possible. Skin failure risk is mitigated by applying coatings that protect the skin fabric from UV radiation. For further research, a Computational Fluid Dynamic (CFD) analysis of the balloon deformation by wind should be performed to investigate stresses in the balloon skin and the change in balloon drag coefficient.

One of the highest risks for the lander mission is the covering of the lander by the balloon skin in case of balloon deployment failure. Should the balloon fail it might come down on the lander, covering solar panels and damaging antennas. In this case the lander mission might be lost. This risk is mitigated by using an inflatable cone to keep the balloon clear of the lander. Another risk to the lander mission is that the lander might be dragged along or toppled over by the forces acting on it via the tether holding the balloon. Should this happen, the lander mission is most likely lost. A shear bolt has been built in the tether to break the connection between the balloon and the lander should the forces become too high.

The taken safety measures should guarantee a low-risk balloon mission.

8. TESTING AND PROTOTYPING

Because a balloon system as proposed here has not been used on Mars before, it is crucial that the feasibility and usefulness of the system is shown. To get familiar with the dynamics of the balloon system a first simple prototype was tested at the Royal Netherlands Meteorological Institute (KNMI). To record temperature, humidity, and pressure a gondola containing a photo camera and measurement devices was suspended below the balloon.

First a tethered experiment was carried out with a tether length of 100 m. From this first test it became clear that the wind influences the balloon system significantly. Not only does the altitude of the balloon decrease due to drag but also the shape of the balloon changes. This balloon deformation could impose large stresses in the balloon material. During the test the gondola containing the instruments was spinning violently, which showed that the stability also is an issue that has to be taken into account.

A free test was carried out up to an altitude of 33 km, where the atmospheric conditions are comparable to those on the Martian surface. Stability of the gondola during the free test proved not to be an issue and it became clear that when stability problems are absent, photographs from such a mission can be very useful for mapping of the surroundings.

Before the balloon system can be operated on Mars further testing and validation is required. Especially the deployment system will require extensive validation, since it is a critical part of the balloon system. Also further testing of the camera gondola suspension is required to reduce spinning.

9. CONCLUSIONS & RECOMMENDATIONS

The study of the Delft2Mars balloon system resulted in two mission concepts that can be performed.

The first balloon concept is able to carry 10 atmospheric packages, distributed along the tether, up to an altitude of 100 m. The packages will measure temperature, humidity and pressure. The total mass of the system is 10.9 kg and the volume is 7.3 L.

The second tethered balloon concept carries a camera to an altitude of 100 m. The camera will take high resolution images of the area surrounding the lander. The system has a total estimated mass of 13 kg, and a volume of 9.5 L.

Both concepts are small and light enough to go along as instruments on future missions like ExoMars and MarsNext. Furthermore, at the International Planetary Probe Workshop (IPPW), the scientific community showed a lot of interest in the two mission concepts, especially in the study of the Martian boundary layer.

The costs per mission concept are estimated to be below € 2 million, which is possible within a university budget. Hence it can be concluded that the Delft2Mars balloon is feasible.

Although the concept is feasible further research is required, there are still questions remaining. A CFD analysis of the balloon will need to be performed, in this way the deformation and lift over drag ratio of the balloon can be better understood. Also, not all instruments are space ready. Therefore, more detailed design, research and cost estimations will have to be performed. The deployment sequence is complex and will require testing to show its feasibility, as does the suspension of the camera gondola to ensure stability.

When the above challenges have been overcome, a balloon mission on Mars has yet come another step closer.

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